

MATERIALS PROCESSING

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MAIN CONDITIONS FOR EFFICIENT DRILLING OF HOLES IN BRITTLE NONMETALLIC MATERIALS USING DIAMOND DRILLS

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It is indicated that in drilling holes in parts made of brittle nonmetal materials, the axial cutting force developed by the drill should be higher than the critical cutting force corresponding to the threshold of the brittle destruction of material. A model of slime removal from the cutting zone is developed ensuring the operation of the drill in the self-sharpening mode. Recommended pressure values for the lubricant-coolant supplied to the inner cavity of the drill are calculated based on the drill diameter.

Brittle nonmetallic materials, such as glass, quartz, ceramics, ferrites, and glass ceramics, find wide application in radioelectronics, machine and instrument building, optics, watch and jewelry production, and construction and household products. These materials have high hardness, strength, and brittleness.

A common labor-consuming operation in making parts from nonmetallic materials is the formation of holes. Diamond drilling [1] is one of the most efficient methods for producing holes of diameters ranging from 0.8 to 1000 mm and more. Without diamond drilling one could not produce microcircuit bases, light guides, laser and optic gyroscopes, spectacle lenses, photodisks, portholes, optical parts, glass fixtures, or mirrors.

Diamond drilling is one of the most stressed grinding processes. Diamond drilling is identical to grinding with the face of a cup wheel. Unlike drills for drilling metals that have screw grooves for chip removal, a diamond drill constitutes a thin-walled ring with undercuts in the body. Therefore, the process proceeds in extreme grinding conditions as follows:

- the cutting end face of the drill is in constant contact with material being treated;
- the automatic removal of slime from the cutting zone (which occurs in circular and surface grinding) is absent;
- cooling of the cutting zone is hard to achieve;
- a core may get stuck in the inner cavity of the drill;
- drilling occurs under forced cooling via the inner cavity of the drill.

The efficiency of diamond drilling is impeded by absence of scientifically justified recommendations on choosing optimum drill parameters and drilling conditions.

A law was developed by Hertz for contact deformations of elastic bodies and experimentally confirmed by Auerbach, according to which

$$P_{cr} = Br,$$

where P_{cr} is the critical load in the formation of a microcrack in a brittle material; B is the Auerbach constant; and r is the indenter (grain) radius.

The Auerbach elastic deformation regularities without visible plastic consequence are valid for indenters radii ranging from 10 μm to 1 cm, i.e., are within the size range of diamond powder grains used to make drills.

Let us formulate the following statements for the diamond drilling process based on the Hertz and Hooke laws taking into account the drilling specifics.

The cutting stress generated by a single diamond grain in the material treated should exceed its brittle destruction strength. This relation taking into account the cutting force and the contact surface area can be written as follows:

$$\sigma_n \geq \sigma_d \rightarrow \sigma_n F_c \geq \sigma_d F_c \rightarrow P_{ef} \geq P_{df},$$

where σ_n are stresses developed in the material and in the grain; σ_d is the brittle destruction strength of the material; F_c is the contact surface area; P_{ef} is the effective cutting force; and P_{df} is the critical cutting force corresponding to the destruction threshold of the material.

The pressure of the liquid supplied to the inner cavity of the drill should be sufficient for removing slime via the ring clearance of the cutting zone and for abrasive wear of the binder.

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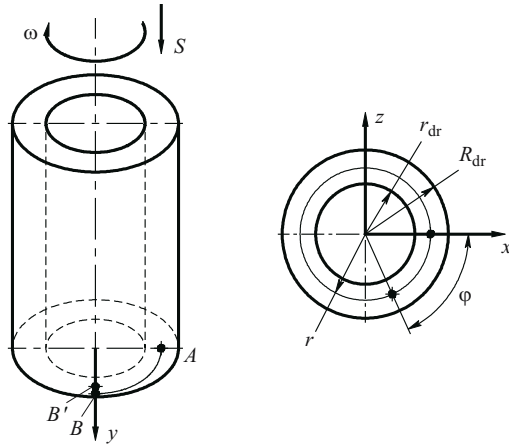


Fig. 1. Kinematics of a single grain in diamond drilling: A , B , and B' are the points of the grain travel; ω is the rotational speed of the drill (min^{-1}).

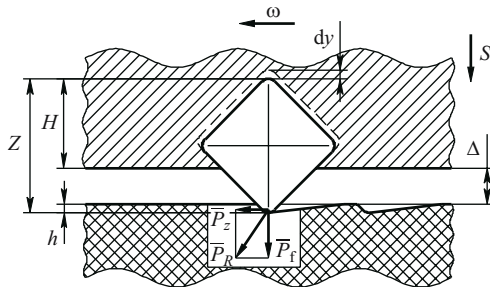


Fig. 2. Scheme of work of a single grain.

Let us analyze the kinematics of a single grain in diamond drilling (Fig. 1). The path of the grain is described by the following system of equations:

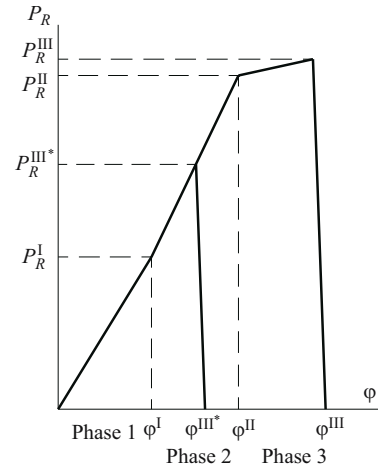
$$x = r \sin \varphi;$$

$$y = \frac{S}{n} \frac{\varphi}{360};$$

$$z = r \cos \varphi;$$

where x , y , and z are the grain coordinates; r is the distance from the drill center to the grain, mm; φ is the drill rotation angle, deg; S is the feed, mm/min; and n is the number of revolutions of the drill per min.

The work of a single grain (Fig. 2) can be represented as follows. A grain Z immersed into a metal binder to a certain depth commits a complex motion into the depth of material being treated. The resultant travel is determined by summing the drill travels as a combined grain – binder system and the travels of the grain itself in contact with the material being treated. In doing so, the grain commits a helical motion sinking into the material treated to a depth of $y = SD\pi/60000v$ per one drill revolution (D is the drill diameter, mm; v is the cutting speed, m/sec).



* Phase 2 may be absent.

Fig. 3. Phases of microcutting process by a single grain.

Figure 3 shows the dependence of the axial cutting force on the drill rotation angle and demonstrates the method for graphical identification of the microcutting process phases for a single grain. It is established that the diamond grain initially slides along the material, after which elastic deformation occurs. Upon contacting the material treated, the protruding surface of the grain incorporates into this material. A system of cutting forces starts acting upon the grain and strives to tear the grain off the binder. This stage of the process will be arbitrarily called (phase 1).

The strength of the material treated exceeds the strength of the binder; however, it is lower than the strength of the diamond grain. Under these conditions the grain deforms the more plastic binder and becomes immersed into it and simultaneously acts upon the material treated (phase 2).

Since the surface deformation process involves brittle destruction, as soon as stresses in the article under treatment achieve a certain critical value, part of the material is chipped up. At the same time microcracks are formed, which facilitates further splitting of chips and is responsible for the formation of defects on the treated surface. Immediately after spalling, the cutting force drops to zero (phase 3) and the grain under the effect of elastic deformation of the binder returns to its original position. Due to the residual deformation of the metal binder material (for instance, M2-01) the setting area of the diamond grain increases by the value dy (Fig. 2). In some cases where the compression strength of the binder exceeds the shear strength of the material of the article, phase 2 may be absent. In this case phase 1 is immediately followed by brittle destruction, for instance in the MonAlit binder. Then the process is repeated. The dependence of the dispersion of the surface of brittle nonmetal materials on cutting force is corroborated by experiments performed on a special testbench with stabilization of axial cutting force.

We investigated the acoustic emission (AE) signals at frequencies of 100 and 200 kHz and the feed and axial cut-

ting force when drilling glass-ceramic plates of thickness 1 mm using a horseshoe-shaped drill of diameter 3 mm from diamond AS20 of grain size 100/80 and concentration 100% produced by the powder metallurgy method on M2-01 binder. The process was implemented with an adaptive control system and operating stabilizable axial cutting forces P_f equal to 35 and 50 N. The acoustograms exhibit variations of the AE signal in time; these variations differ for frequencies of 100 and 200 kHz.

In the first case with an axial force of 50 N the drilling process proceeds with a constant feed, which for this operating regime is 10 mm/min, a constant cutting force, and a constant amplitude of AE.

In the second case with a force of 35 N the removal is absent, and we observe fluctuations of the cutting force and attenuation of AE parameters due to the absence of micro-cutting processes. Such course of the process is artificial. It is quite regular, since in the second case the stabilizing cutting force P_{ef} is lower than the estimated critical cutting force P_{dr} causing the destruction of the material, which for this case is equal to 40 N.

Figure 4 shows the dependence of axial force on feed in diamond drilling of different materials. The experiments were carried out on a KIP vertical milling machine (Makino Company, Japan) using horseshoe-shaped drills of diameter 4 mm made of synthetic diamonds AS50 of graininess 160/125 on the M2-01 binder. Drilling is performed at rotation speed of the spindle equal to 4000 min^{-1} . It can be seen that the S/P_f for different materials is a constant value. In the general case, the lower the force that has to be applied to remove an allowance unit, the higher is the cuttability of the drill; the higher the drilling intensity under a constant axial force value, the better the cutting properties of the tool. Therefore, the criterion of the diamond drill efficiency could be the cuttability coefficient, which is the ratio of the linear efficiency (feed) of drilling to the axial cutting force (mm/(min · N)):

$$K = \frac{S}{P_f}.$$

The physical meaning of the cuttability coefficient is interpreted as the unit intensity of abrasive grinding.

Thus, the main factor providing for removal of material is the axial cutting force in the zone of the contact of the tool with the material being treated.

As the diamond drilling process requires the removal of slime from the treatment zone, its volume was calculated. It is known that destruction of brittle materials is closely related to the crack formation mechanism. The material under treatment is destroyed precisely due to the origination and propagation of cracks.

Three types of cracks are formed in microdestruction: median C_M , lateral C_L , and conical C_C (Fig. 5). For various materials the order of formation of cracks may differ slightly;

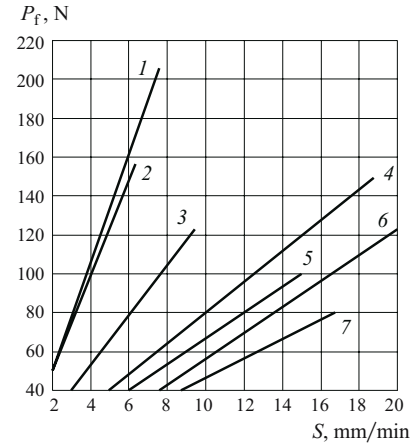


Fig. 4. Dependence of axial cutting force on feed in diamond drilling of different materials: 1) ceramic TsM-332; 2) ceramic 22KhS; 3) quartz; 4) technical glass; 5) glass ceramic ST-32; 6) glass ceramic ST-38; 7) ferrite 1000NN.

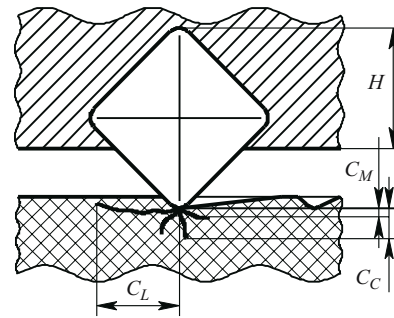


Fig. 5. Cracks determining spalling size.

however, for the main brittle materials considered in the present study this sequence is as follows. First, median cracks arise at the boundary of the single grain. When the load is lifted (as a consequence of spalling or the grain being torn away), these cracks reach the surface. Then after an increased load or its complete removal, lateral cracks arise under the effect of residual stresses. Conical cracks may originate under large feed values, when the single grain is indented into a surface treated by the shock method. Such cutting conditions are not discussed below. Evidently, some material is chipped up after the emerging cracks intersect with each other. Thus, the size of spalling (an elementary chip) depends on the length of lateral cracks and the depth of the defective layer depends on the size of median and conical cracks.

The crack resistance measure is the critical coefficient of stress intensity k_c proportional to the critical stress under which a crack of length C is formed:

$$k_c = \sigma_c \sqrt{\pi C},$$

where σ_c is the critical stress of crack formation.

It was established during experiments [3] that the lateral crack in the diamond drilling of brittle materials can be calculated from the formula

$$C_L = \left(\frac{P_f^{sg}}{k_c} \right)^{3/4},$$

where P_f^{sg} is the axial force on a single grain.

Considering the small linear sizes of the cracks determining chip sizes, the volume of the material in a single chipping can be represented as a triangular prism with height and width equal to the length of the lateral crack:

$$V_{ch}^{sg} = \frac{C_L^3}{2}.$$

As a result of modeling, the volume of material dispersed per one revolution of the drill was determined as

$$V_{ch}^{rev} = 2.3 \left(\frac{P}{k_c n_m^c} \right)^{3/2} \pi R_{dr} n_m^c,$$

where P is the axial cutting force; n_m^c is the number of cutting grains; R_{dr} is the drill radius.

To study the work of a group of grains fixed in the binder in drilling (not only in microindenting), additional experiments were carried out drilling quartz and glass K8 at different feed velocities, with microphotos of the drill surface taken at different stages of its operation. Drilling was performed using a drill of diameter 26 mm, graininess 160/125, on binder M with concentration 150%, feed of 28 mm/min, and spindle rotational speed of 2500 min⁻¹.

The study of microphotos using a MBS-2 stereoscopic microscope provided a spatial estimate of the situation observed.

It was found that in a favorable drilling mode the article surface has no contact with the binder. The depth of the layer removed per one revolution of the drill at the specified conditions is 10 – 20 μm. Consequently, with the average grain size equal to 141 μm (graininess 160/125) its front face (average embedding 50%) is immersed into glass to 0.15 – 0.30 of its protruding part, whereas a clear space 40 – 45 μm high persists between the binder and the article surface, sufficient for them not to contact. This space is continuously filled with moving chips of the article and torn-away grains. The emerging layer passes with a certain effort between the article surface and the drill end face and wears the binder by its abrasive effect. As a result of this process, the binder surface between the grains seems rough.

When material is removed in intensified conditions (an increased feed velocity or intensified axial force under gravitational feed) where grains become indented to a deeper depth, the binder may enter into direct contact with the article. The grains in this case experience perceptible overload-

ing and are intensely destroyed or blunted. In the case of slow abrasion of the binder, which is related to an insufficient abrasive effect of the bottom surface of the hole in the article on the binder surface, new grains do not have enough time to be bared and together with the binder form an even surface, which as a result of inevitable and yet slight heating caused by friction becomes smooth and even polished. The tool stops working and is usually believed to become greased. However, in this case the phrase does not reflect the true physical meaning of the phenomenon, because in fact the tool becomes blunted.

Another phenomenon is observed in the case of insufficient lubricant-coolant pressure and insufficient cooling of the contact zone, when due to intense heating caused by the friction of grains against the binder (work under elastic deformations) some chips of the treated material soften (this is true especially true of glass and glass ceramics) and tightly pack spaces between the grains, thus impeding the abrasion of the binder. In this case as well the self-sharpening process stops, the drill end is greased, and it stops functioning.

Finally, in an emergency, when the feed abruptly increases or cooling suddenly stops, the drilled area may be heated to such a temperature that the binder material may melt or the material of the article may soften. In this case the diamond grains become covered by the melted metal film, the tool is greased and stops working, and the diamond-bearing layer may be destroyed.

Comparing the possible drilling variants, the conclusion can be made that the optimal operating conditions for the tool imply a clearance existing between the article material and the binder surface (Fig. 2):

$$\Delta = Z - (H + h),$$

where Δ is the working clearance; Z is the graininess; H and h are the depths of embedding and indentation of the grain.

In this case drilling products are properly removed from the cutting zone, the cutting zone is intensely chilled and lubricated, and the binder wears due to the abrasive effect of the drilling products, which creates favorable conditions for self-sharpening of the tool.

The operating mode with self-sharpening of the drill is possible if the particles of dispersing material uniformly wear the binder and new diamond grains become bared at a proper moment. Consequently, a variation of the coolant-lubricant pressure parameter is an extreme factor. In the case of intense washing out of slime (increased pressure and flow rate), intense self-sharpening does not occur. Accordingly, after a few cycles of drilling the tool requires dressing. On the other hand, in the case of insufficient washing off of slime (decreased pressure and flow rate) the tool becomes greased, the temperature in the cutting zones grows, and an emergency failure of the tool may occur.

Taking into account the above factors, let us determine the lubricant-coolant pressure for the inner supply scheme (the most advanced and widely used in drilling).

Figure 6 shows the scheme of a ring drill and the main geometrical parameters affecting the lubricant-coolant pressure. A certain volume of disperse material is formed in drilling and has to be removed from the cutting zone. The pressure of the coolant-lubricant mainly depends on this volume.

It is clear that slime should not be removed from the cutting zone all at once. This paradoxical fact has the following explanation. If all slime is removed from the cutting zone at once, there is no abrasive wear of the binder, i.e., no self-sharpening of the tool. Under normal conditions of diamond drilling, the binder surface does not contact the surface of the article treated, and the coolant-lubricant passes through the available clearance and thus cools and moistens the cutting grains and the article surface. If there is no abrasive wear of the binder, the grains work until the full wear of their protruding surfaces, and then the binder surface will contact the article surface, causing intense heating of the cutting zone and an increased load, which will finally lead to the fusion of the binder and abnormal end of drilling. The tool will require additional dressing. Therefore, the determination of the optimal coolant-lubricant pressure is an essential factor of the self-adjustment of the drilling process.

The pressure is optimal when not the total volume of disperse material V_{ch}^{rev} is removed from the cutting zone per one revolution, but only a part of that volume V_{sp}^{rev} . As a result, the coolant-lubricant pressure has been determined as follows:

$$P_{CL} = \frac{k(V_{ch}^{rev} - V_{sp}^{rev})[(D_{dr} + 2\Delta + \delta_r)^2 - D_{dr}^2]}{4F_{cb}d_{dr}(\Delta + \delta_a)^2},$$

where k is a coefficient depending on the type of coolant-lubricant; D_{dr} and d_{dr} are the outside and inside diameters of the drill; δ_r and δ_a are the radial and axial run-out of the drill; and F_{cb} is the total area of the contact between the binder and the disperse material.

Practical recommendations for choosing the coolant-lubricant pressure depending on the diameter of the hole drilled obtained by calculations are given below.

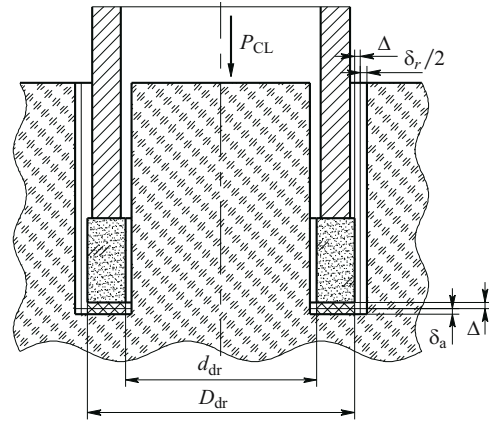


Fig. 6. Main geometrical parameters affecting coolant-lubricant pressure.

Drill diameter, mm	Lubricant-coolant pressure, MPa
1 – 5	0.30 – 0.50
6 – 10	0.20 – 0.40
11 – 20	0.15 – 0.25
21 – 40	0.05 – 0.15
41 – 100	0.02 – 0.10

Thus, to ensure drilling of holes in brittle nonmetallic materials, the axial cutting force developed by a diamond drill has to be greater than the critical cutting force corresponding to the brittle destruction threshold of the material.

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